Rock   Slope   Engineering

PART C

APPROACH AND TECHNIQUES IN GEOLOGIC

STRUCTURAL ANALYSIS

by

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PREFACE

This reference manual was prepared by Dr. D.R. Piteau and Associates, British Columbia, in conjunction with a series of Rock Slope Engineering Workshops sponsored by the Implementation Division of the Federal Highway Administration.

The manual consists of eight main parts as follows:

Part A: Engineering geology considerations and basic approach to rock slope stability analysis.

Part B: Methods of obtaining geologic structural, strength and related engineering geology data.

Part C: Approach and techniques in geoloic structural analysis.

Part D: Slope stability analysis methods.

Part E: Rock slope stabilization, protection and warning - instrumentation measures and related construction considerations.

Part F: Blasting for Rock Slopes and related excavation considerations.

Part G: (Field Manual) Description of Detail Line Engineering Geology Mapping Method

Part H: (Appendix) Chapter 9 of Landslides; Analysis and Control (TRB Report 176)

A precise Table of Contents is given in each part of the manual. Acknowledgement of those who have provided assistance is given in Part A of the manual.
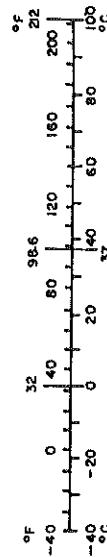
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m³	cubic meters	35	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

Temperature scale:

°F -40 0 32 98.6 212
°C -40 -20 0 20 37 40 60 80 100

<u>PART C</u>

<u>APPROACH AND TECHNIQUES IN GEOLOGIC</u>

<u>STRUCTURAL ANALYSIS</u>

<u>PRACTICUMS</u>

PART   C

APPROACH AND TECHNIQUES

IN GEOLOGIC STRUCTURAL ANALYSIS

1.   INTRODUCTION

Described in the following are the basic methods and approach that is taken
to delineating basic areas of similar geologic structural conditions for
purposes of carrying out a rational slope stability analysis.   The funda-
mental steps leading to selection of structural domains are discussed as is
the plotting, processing and interpretation of the raw geologic structural
data.

The use and application of the stereographic net is fully described and
appropriate examples all developed in the practicum to fully illustrate
these applications.   Typical case histories have been included in the
practicums which depict typical geological environments where workers might
be required to analyze and design rock slopes.

2. BASIC STEPS IN DELINEATION OF STRUCTURAL DOMAINS AND DESIGN SECTORS

2.1 REGIONAL GEOLOGY ASSESSMENT AND REVIEW

The first stage in the geologic structural assessment is to assess the regional geology of the area. A complete review should be made of the owners, agency, etc. own files as well as relevant published geological information of the area. A few public sources, as well as some private reports, of geological information may be available and relevant to the problem. Many of these sources contribute to a national catalogue, regional records, index of geosciences data, etc.

Geological maps may be supplemented with aerial photographs of the area, which can be obtained from airphoto libraries, etc. More restricted collections of photography are available from provincial and state governments and from private sources. Aerial photographs are useful in planning field work, in detecting naturally unstable slopes, locating prominent linear features and providing a general overview of the regional geology of the area.

Before detailed structural surveys are initiated at the site, conventional reconnaissance geological mapping should be conducted to assess basic rock types, delineate major geological structures, such as faults, dykes, lithological contacts, etc. and any other features that represent major discontinuities in the area. In this regard, major discontinuities include any features which are of the scale of the proposed slopes. Plane table, airphoto and other techniques, as they apply, may be used to assist with this mapping.

2.2 PRELIMINARY DETERMINATION OF STRUCTURAL DOMAINS

Having acquired a general appreciation of the geology in the project area the next step is to estimate which particular sections of the rock mass can be subdivided into preliminary structural domains according to the disposition of major structural features in the site area.

2.3 DETAIL GEOLOGICAL MAPPING

Once delineation of preliminary boundaries of structural domains has

been carried out and sufficient knowledge of the site geology has been acquired, a suitable detail mapping program, tailored to the site conditions, can be established. A geologic map of some kind may already exist on the property resulting from early exploratory work, but rock engineering data probably will be scarce. General geologic mapping could be carried out somewhat independent of more detailed engineering geology mapping. Thus, two distinct mapping programs may be ongoing. To maximize on this situation a concerted effort should be made to have both mapping efforts compliment one another. The main objective of this phase of the work is to prepare a map of (a) minor structural features, (b) major structural features and (c) lithological distribution which can be used to assist in structural reassessments.

2.4 RE-EVALUATION OF STRUCTURAL DOMAINS

Having acquired information relating to the distribution of minor structures, major structures and lithology, the preliminary boundaries of the structural domains can be re-assessed. At this stage additional structural analysis and data processing may be required to redefine these boundaries. Structural data from different parts of structural domains can be compared at this stage to test for structural similarity within structural domains. This analysis work could lead to a substantial revision of structural domain boundaries.

2.5 DETERMINATION OF GEOLOGIC STRUCTURAL CHARACTERISTICS IN STRUCTURAL DOMAINS

Once the boundaries of the various structural domains have been redefined, attention should be given to delineating the joint sets within each structural domain and determining the characteristics, including the attitude, geometry and spatial distribution of each joint set.

Attempts should be made to determine the general characteristics of joints as a whole to establish average properties of the joints within structural domains. Also, to sort out (if possible) the joints of different genetic origin (i.e. shear as against tension features, etc.) and to determine the characteristic features of the various types of discontinuities (i.e. characteristics of cross joints, bedding joints, geological contacts, schistosity, etc.).

The joint data for each structural domain should be analyzed separately and sorted in plots according to the various properties of the joints which were recorded. From these plots the percentage of joints in the set having

any one property can be determined. This is achieved by counting the
number of joints in that set with that particular property and comparing
it with the total number of joints in the set.

2.6 FINAL DETERMINATION OF STRUCTURAL DOMAINS

It will be noted that the initial delineation of structural domains is
based on the attitude of the structural features only. However, desig-
nation of a structural domain implies that the joint population within
the structural domain is similar with regard to geometry (i.e. asperities,
size, infilling) and spatial distribution (i.e. spacing, etc.) as well as
attitude of the structural features. As a consequence of joint property
determinations described above, it may be found that within a structural
domain the properties vary substantially from one part of the mass to
another, and that the structural domain boundaries should be re-established.

It is seldom economically feasible to investigate the characteristics of
all parameters within a structural domain. Experience has shown that within
a joint set of similar attitude the structural characteristics are usually
similar and are not usually investigated. If the joint properties in a
particular set are found to vary from one location to another in the rock
mass, depending on the parameters which vary and the extent of variation,
it may be necessary to include these parameters in structural domain
assessment.

2.7 DETERMINATION OF DESIGN SECTORS

Having defined the structural domains the next step is to examine the site
in terms of its slope geometry and delineate straight segments of slope.
Straight segments of slope subdivide the area into sections which, when
overlapped with the structural domains, give design sectors.

The design sectors therefore represent sections of the slope which have
both similar orientation as well as statistically similar geologic
structural properties. The analyst is now in a position to determine
failure modes which are kinematically possible in each design sector.

3. GEOLOGIC STRUCTURAL ANALYSIS OF ORIENTATION DATA USING STEREOGRAPHIC PROJECTION

3.1 INTRODUCTION

Three dimensional problems in structural geology can be solved by descriptive geometry, trigonometry or stereographic projection. Stereographic projection is used in most cases because it is much faster and provides more relevant information than other structural analysis methods. Although it is impossible to represent distance on stereographic projections, they can be used to illustrate geometrical relationships, distribution and genetic significance of structural populations.

With respect to attitude in structural analyses, one either deals with planes (i.e. two-dimensional surfaces such as faults, shears, joints, cracks, unconformities, geological contacts, axial planes, bedding, cleavage, foliation, etc.) or lines (i.e. one dimensional features such as lineations, plane intersections, fold axes, etc) which have a specific orientation in three-dimensional space. Analysis of combinations of two or more distinct structural features, whether they are lines or planes which have different orientations, presents a three-dimensional problem which can be solved most simply by the application of stereographic projection.

3.2 PRINCIPLES OF STEREOGRAPHIC PROJECTION

The basic application of stereographic projection is to represent three-dimensional structures in their relative orientation on two-dimensional plane paper. The method used is to project the intersection of structures (i.e. lines or planes) with the surface of a representational sphere, which has its centre on the structure, unto the diametral plane (i.e. horizontal or equatorial plane) of the sphere (see Fig. C-1 (a to c). The intersection of a plane, which passes through the centre of the sphere, with the surface of the sphere forms a great circle. The intersection of a line with the sphere forms two points. By convention only the lower hemisphere of the sphere is used and intersections are projected up to the diametral plane. If projections are made from the intersection

(a)

PLANE OF
DRAWING

ZENITH

P' r

LOWER REFERENCE
HEMISPHERE

$$r = R \sin \frac{a}{2}$$

(b)

LINE OF
IMAGINED
PROJECTION

P' r

FIRST PROJECTION P TO P'
$$r' = 2R \sin \frac{a}{2}$$

THEN REDUCTION TO PLANE
OF DRAWING P' TO P"
BY $r = \frac{r'}{\sqrt{2}}$

$$r = \sqrt{2}\ R \sin \frac{a}{2}$$
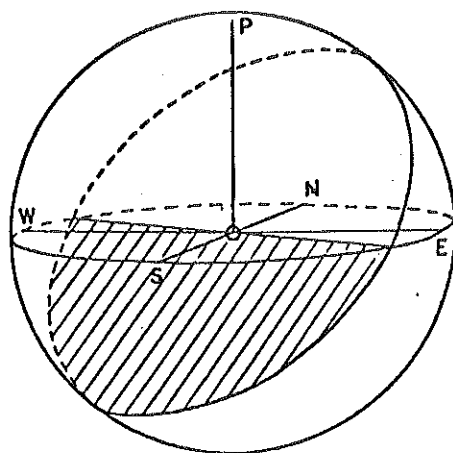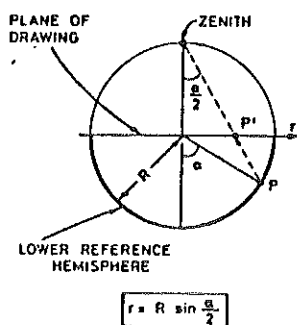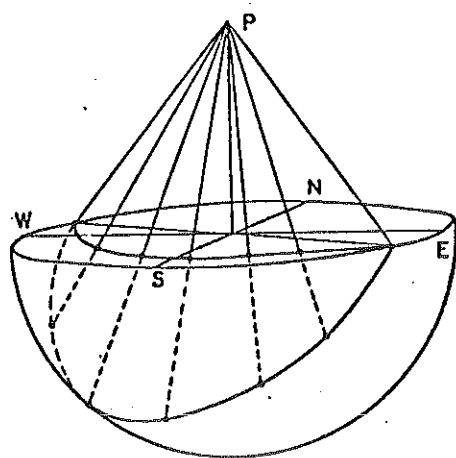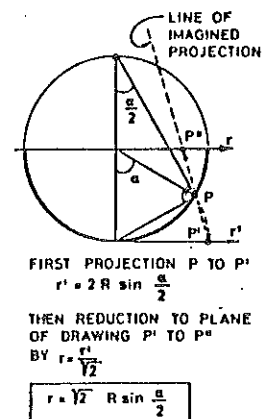
(c)

Fig. C-1 - Principles of Stereographic Projection

    (a)   Spherical projection of a plane

    (b)   Equal angle stereographic projection of the plane in (a)

    (c)   Equal area stereographic projection of the plane in (a)

(after Phillips, 1971 and John, 1968)

of the structure on the sphere to the zenithal pole (P) the result
is an equal-angle projection on the diametral plane (see Fig. C-1).
If the dip circles are spaced proportional to their distance
(chord distance) from point P, we get an equal-area projection
(see Fig. C-1).

3.3   DESCRIPTION OF THE STEREONET

Stereographic projections and structural analyses are generally
facilitated by use of a stereonet which is a grid of the principle
strike and dip lines on the surface of the lower hemisphere of a
reference sphere which has been projected onto the diametral plane.
The grids are constructed so that all possible intersections of a
plane with the lower hemisphere can be accurately projected onto the
diametral plane by the two methods described above.   The grid consists
of projected meridians or great circles corresponding to the various
dips of the plane and small circles which are projected latitude lines
obtained from plunge lines at various angles lying within the refer-
ence plane.   The equal-angle steronet and equal-area stereonet are
shown in Figs. C-2 and C-3 respectively.   Azimuth or strike is plotted
from 0° - 360° on the periphery of the net and dip is plotted from
0° - 90° from the periphery to the centre of the net.

The Lambert-Schmidt equal-area net is the most versatile of the two
stereonets because it can be used for true random statistical eval-
uations of joint populations by density contouring.

3.4   METHODS AND USE OF THE STEREONET

The most efficient method of plotting and analyzing structures by
stereographic projection is by using a transparent overlay of the
net which is fixed by a pin through the centre in such a way that
the overlay is free to rotate.   The overlay carries the outline of
the stereonet and a north point for reference when plotting.   The
overlay can then be rotated so that the strike of any plane or the
azimuth of any line can be plotted by stereographic projection in its
true orientation on the overlay.

Intersections of structural features can be described by planes, lines
or points;   therefore the method of plotting each are required.   The
various parameters of planes and lines as they occur in three-
dimensions or on a stereonet are shown in Fig. C-4.

C-8
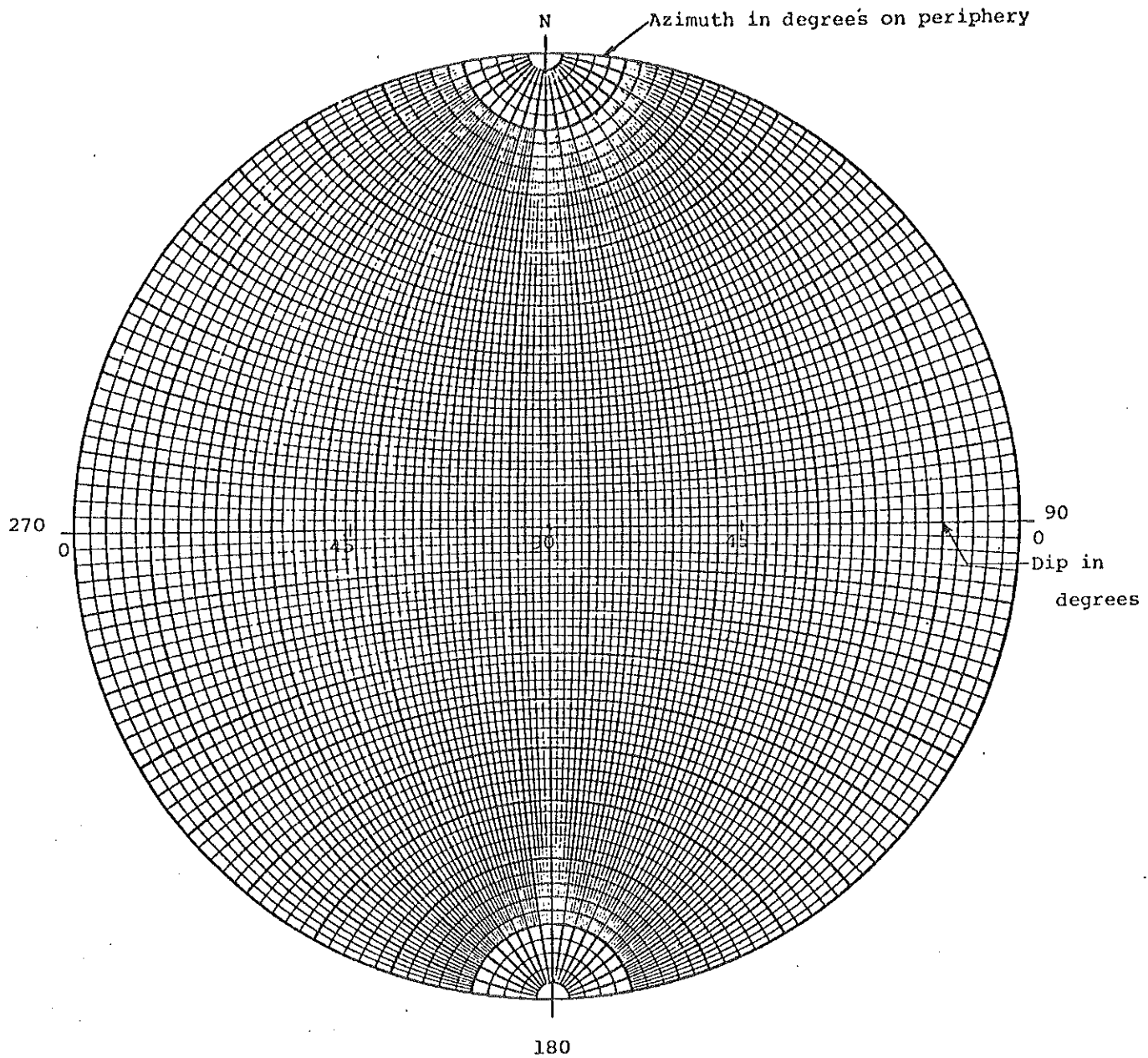
Fig. C-2 - Equal angle stereonet or Wulff net (after Ragan, 1968).
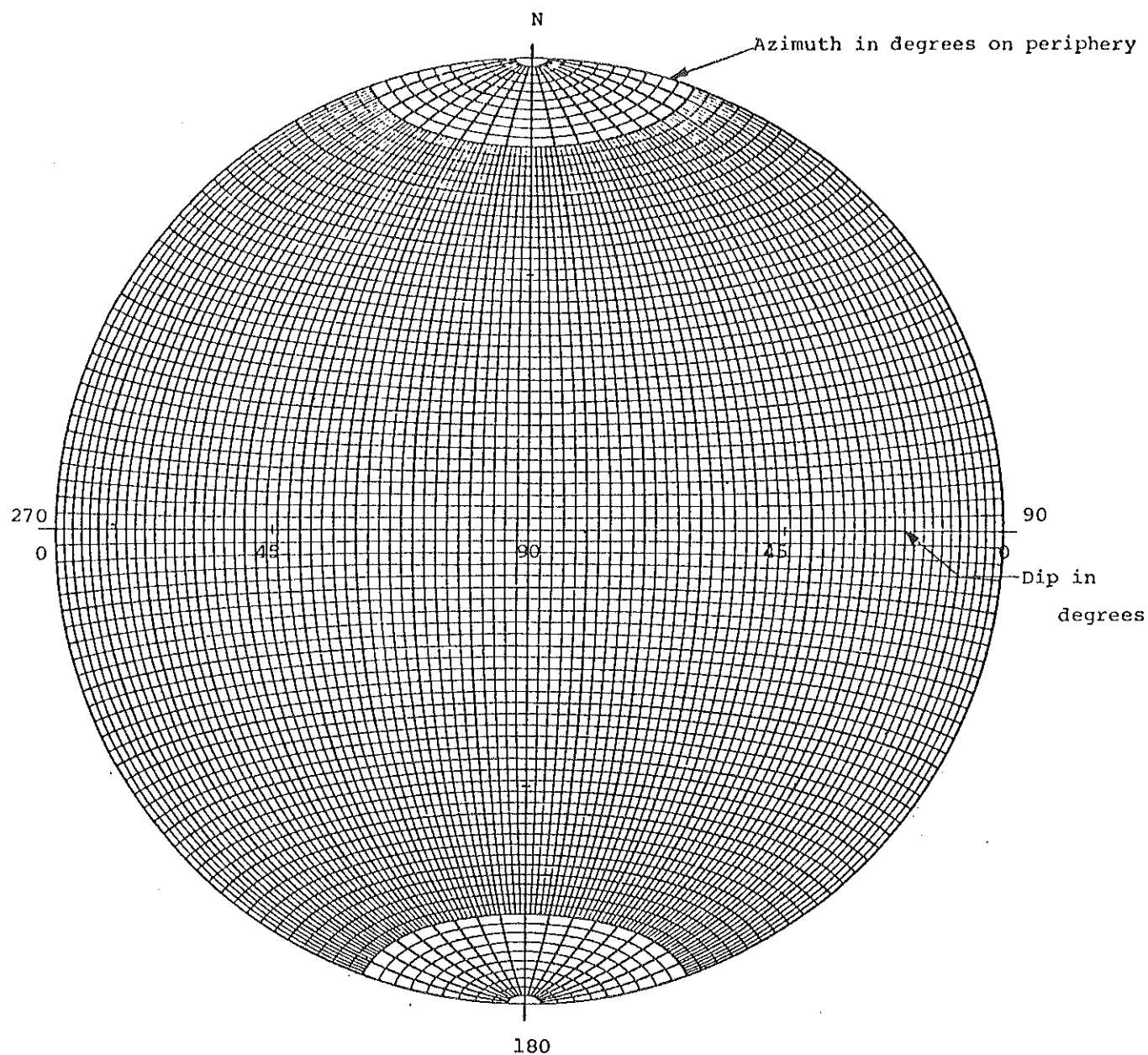
Fig. C-3 - Equal area stereonet or Lambert-Schmidt stereonet
(after Ragan, 1968).
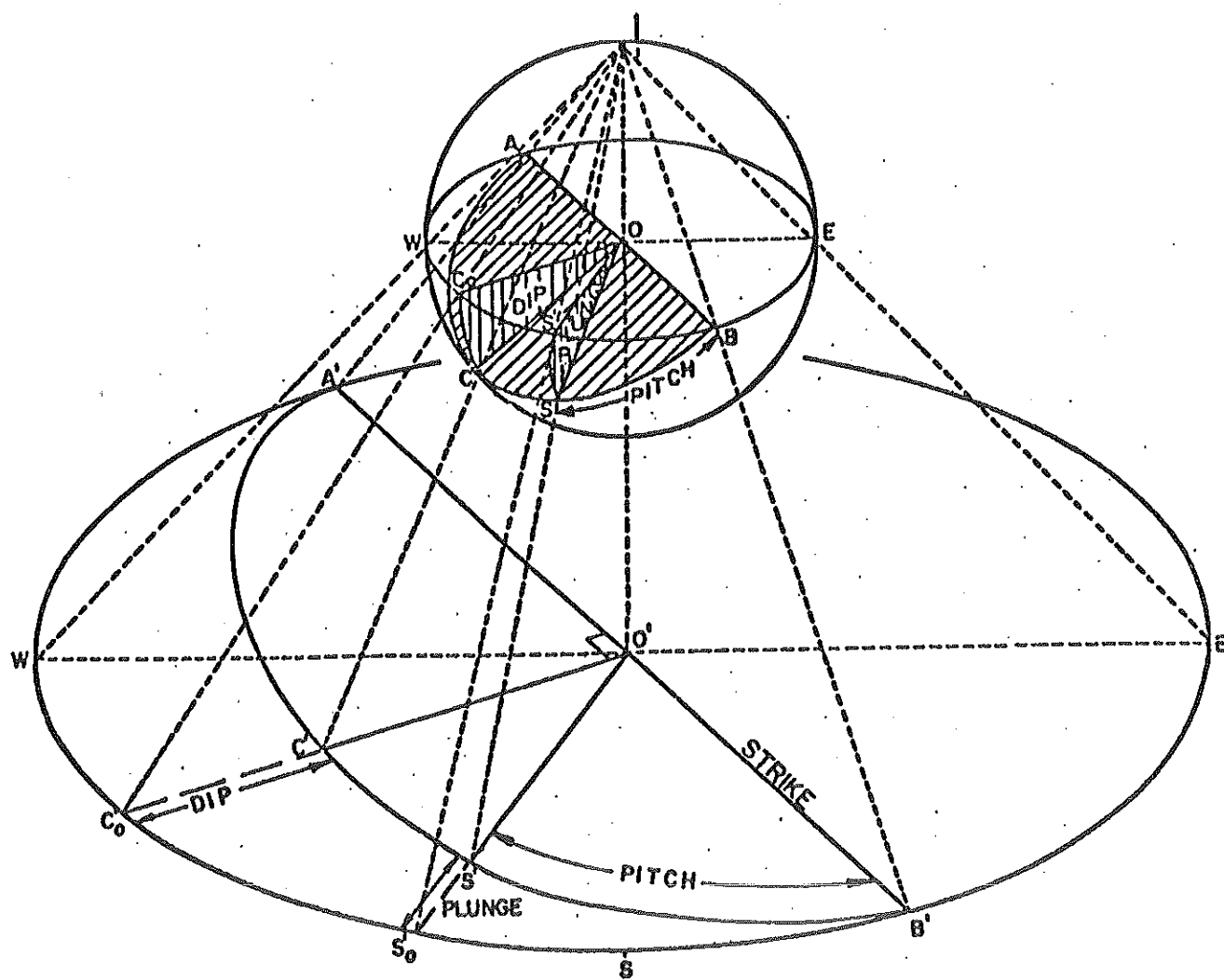
Fig.C-4 — The related use of the stereonet construction to the graphical presentation of dipping planes with a known orientation (after Donn and Shimer, 1958).

3.4.1 Plotting Planes

The attitude of any plane is plotted as if the plane passed
through the centre of the sphere. The projection of the
plane or the projection of the normal or pole to the plane
may be plotted depending on the requirements of the analysis.
As shown in Fig. C-5 (a) the plane is plotted by rotating the
overlay until the strike direction of the plane corresponds
to the north-south direction of the stereonet and tracing on
the dip of the plane. Normals or poles to the plane are
plotted as points along the east-west axis exactly 90° from
the meridian containing the plane. These points are pro-
jections of the intersection of lines normal to the plane
passing through the centre of the sphere and intersecting the
surface of the lower hemisphere, or dip lines.

3.4.2 Plotting Lines and Points

To plot lines the overlay is marked on the periphery of the
net at the azimuth of the line and then rotated to the east-
west or north-south axis of the stereonet where the plunge is
plotted. The line is represented stereographically by joining
the centre of the net and the plotted plunge value as indicated
in Fig. C-5 (b). Points are considered at the intersection of
a line with the lower hemisphere and can be plotted accordingly.

3.4.3 Determination of the Line of Intersection of Two Planes

The intersection of two planes is a line which passes through
the centre of the projection and intersects the surface of the
sphere where the two planes intersect. The attitude of the
line (i.e. plunge and azimuth) can be measured as indicated in
Fig. C-6.

3.4.4 Determination of Angular Relationships

Measurement of true angles between two planes are made in the
plane which is normal to both planes. The poles of the planes
are placed in the same plane by rotating the overlay so that
the poles to the planes lie on the same great circle. The angle
between the planes is the angle between the poles. Angles
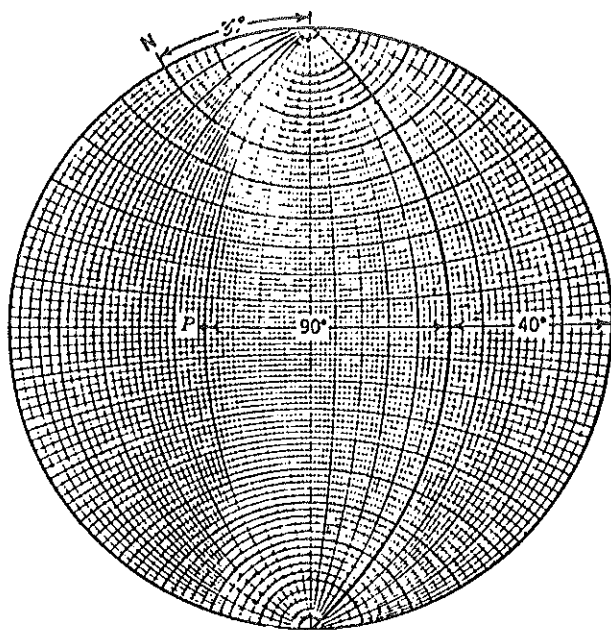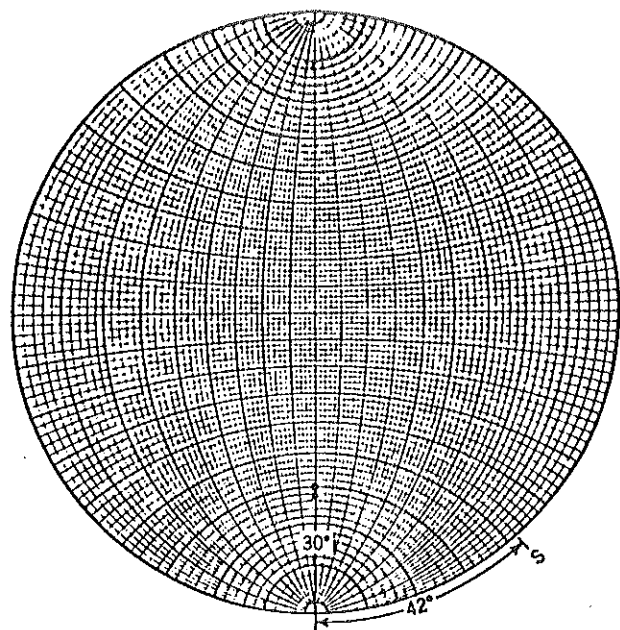
(a)   (b)

Fig. C-5 – Plotting (a) plane – strike NS, dip 40° E

(b) lines – strike NS, plunge 30° S

(after Ragan, 1968).
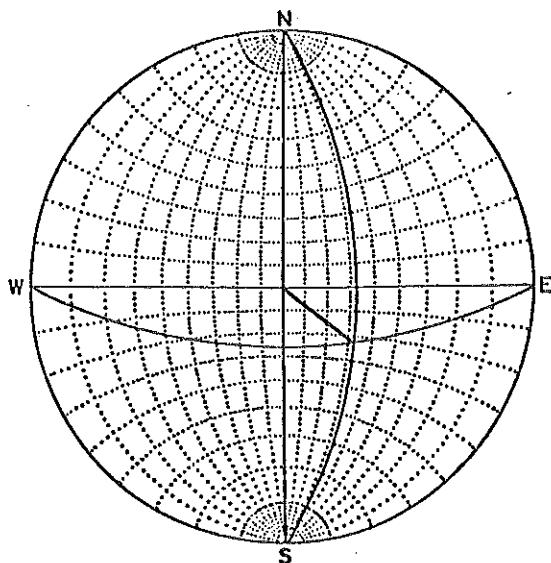
Fig. C-6 – Determination of the line
of intersection of two planes
(after Phillips, 1971).

between lines and/or planes are measured by placing lines and/or poles on the same great circle and measuring the angle as described above.

3.5 USE OF THE STEREONET TO DEFINE STRUCTURAL POPULATIONS

Contouring methods are used to define the peak orientation and distribution of individual populations. Lambert-Schmidt nets must be used to contour poles because all areas within the projection of the lower hemisphere are equal.

Contouring, by convention, employs a counting area equal to one per cent of the total area of the stereonet. All poles occurring within the counting area are recorded as the area is moved to various locations on a grid placed over the stereonet. Several contouring systems are in use but the easiest to set up is the Schmidt method (Phillips, 1971) which employs a square grid and a circular counting area on a cardboard or plastic template as indicated in Fig. C-7 (a and b). Another contouring method, the Kalsbeek method (Ragan, 1968) uses a hexagonal counting area on a set grid, hence the circular template is not required (see Figs. C-8 and C-9).

Contouring is done by recording the number of poles occurring within the counting area at each location and calculating the percentage of total poles occurring at that point. The net is then contoured as shown in Figs. C-7 (c), using a convenient contour interval or number of contours (generally six or less).

Contouring by this method defines the attitude of the maximum concentration of poles and the distribution or dispersion of each population examined. "It has been observed that the ranking of sets cannot necessarily be done on the basis of relative intensity; it is considered prudent to take the results of the contouring and then make a visual judgement in the field on the ranking of sets with respect to their dominance or practical significance" (Coates, 1969).
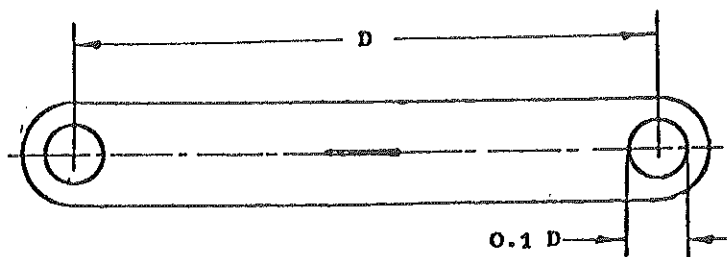
(a)
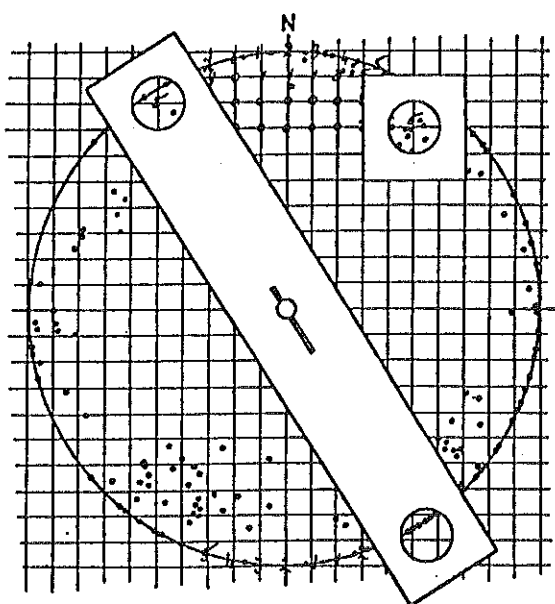
(b)
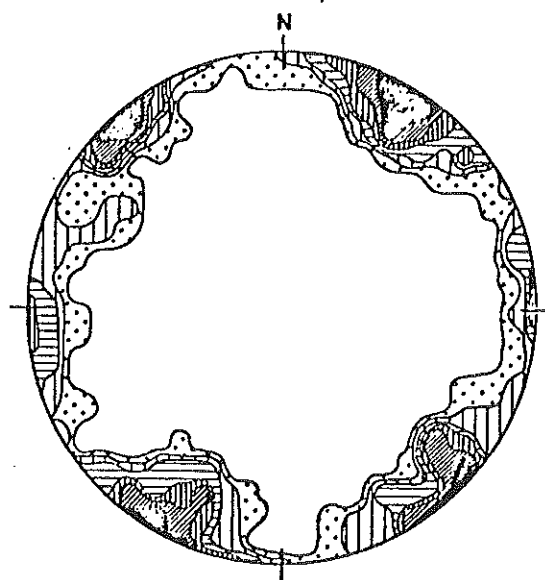
(c)

Fig. C-7 - Schmidt contouring method

   (a) point counter with circular areas of 1.0% of
       total area of stereonet

   (b) use of counter and grid (after Phillips, 1971).

   (c) the projection of (b) contoured and shaded (after
       Phillips, 1971).
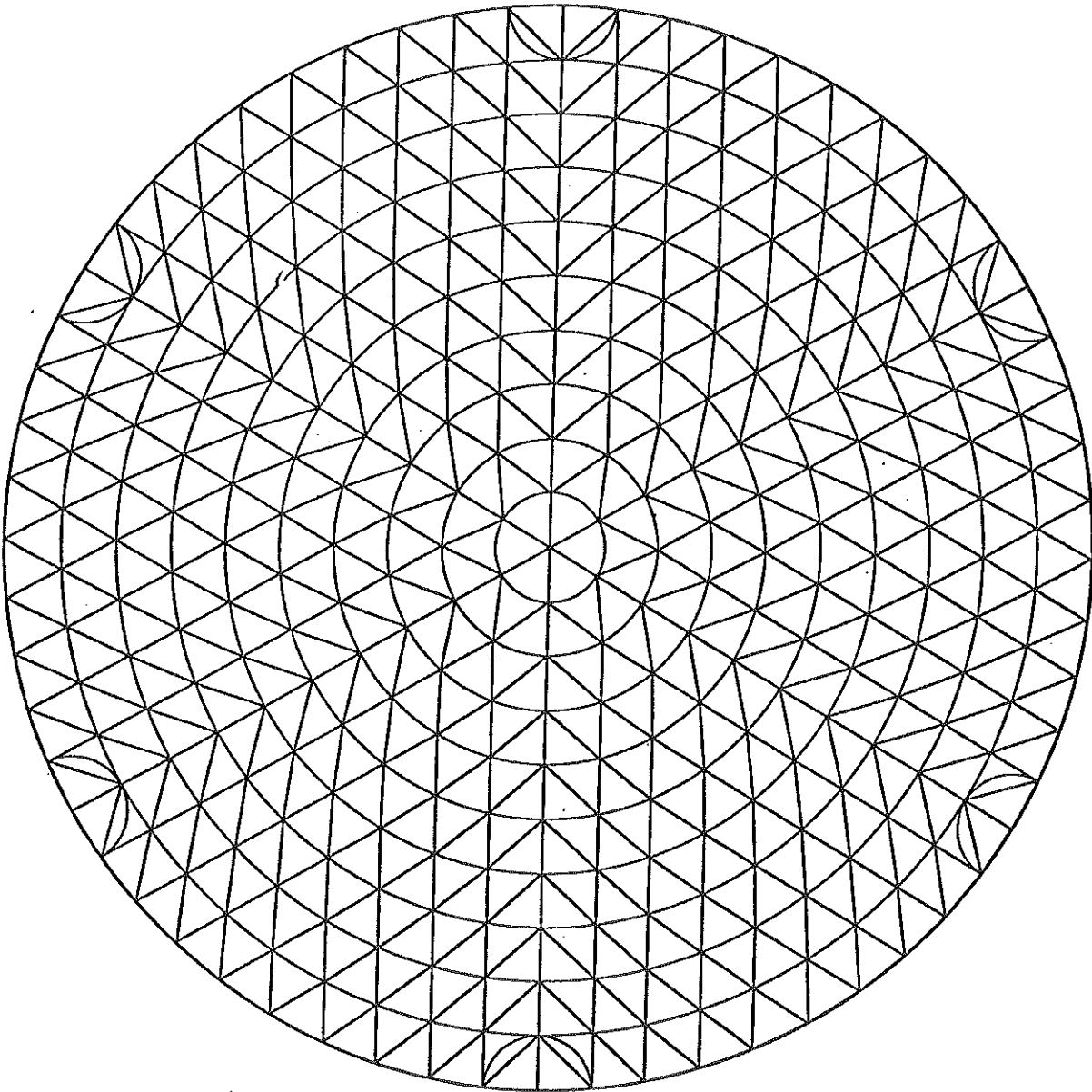
Fig. C-8 - Kalsbeek counting net (after Ragan, 1968).
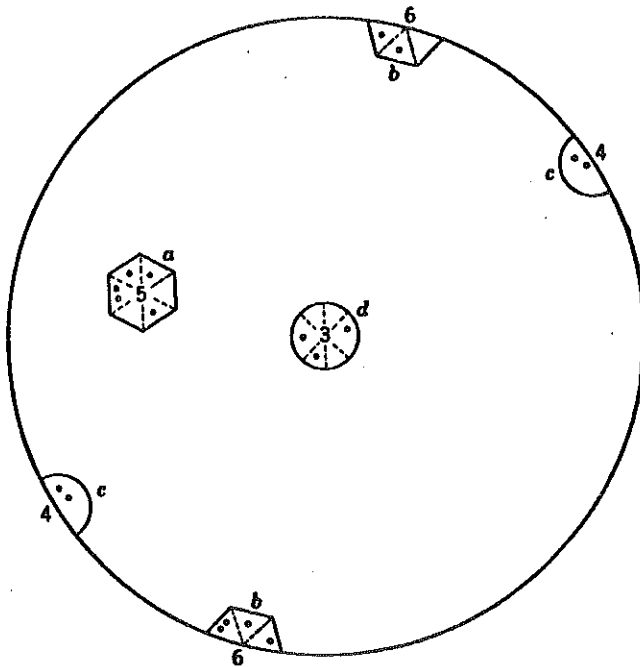
Fig. C-9 - Several special cases of density counting with
the Kalsbeek counting net (after Ragan, 1968).

4. STRUCTURAL DOMAINS

4.1 DESCRIPTION OF A STRUCTURAL DOMAIN

For slope design and stability analysis purposes it is necessary to divide the rock mass or slope into sections of similar geologic structural and lithological characteristics. Sections of the slope having approximately similar structural characteristics are designated *structural domains*. Systematic sets of joints occurring with each structural domain which have been selected for consideration in the design calculation and related evaluations are called *design joints*.

For slope engineering purposes designation of a structural domain, therefore, implies that the volume of rock mass or section of slope so designated has a geologic structural population which is approximately similar or homogeneous in a statistical sense with regard to attitude, geometry and spatial distribution. This includes important parameters such as continuity, intensity, joint wall asperities and infilling or gouge characteristics. This means that a sample of the structural properties of the rock mass will not differ significantly in a geologic structural sense from another sample taken from a different part of the same structural domain. Hence, one can predict, within limits, the structural properties of the rock mass over the whole structural domain from a sample taken from only part of it.

Each structural domain must be considered separately for its particular stability characteristics in the slope. Hence, a slope design suitable for one part of the area in a particular structural domain may not apply to another area located in a different structural domain which has different mechanical and physical properties.

4.2 CONTROLLING FEATURES AND CONSIDERATIONS IN DEFINING STRUCTURAL DOMAINS

Structural domains vary in size so that a project site could contain one or several structural domains. It is not uncommon in complex geological environments, for example intensely folded and metamorphosed sequences involving several phases of intrusion, that several structural domains exist. On the other hand, in areas developed in essentially undeformed rock, such as large stocks or plugs involving one phase of

igneous intrusive rock, the geology is generally less complex with
the result that the geology is more uniform and fewer structural
domains exist.

Should the methods of analysis not be entensive enough to discern the
variation in characteristics of each of the important structural para-
meters in the rock mass (i.e. continuity, intensity, joint wall
asperities, etc.), it may be necessary to make a very basic assumption
to overcome this limitation and thus limit the investigation to one
parameter only.   If one assumes that all joints in a particular set
result from a similar set of conditions, namely similar tectonic and
stress history, etc., then there is the likelihood that all joints
from a single joint set would be similar in a statistical sense.
Thus, similarity of one property is assumed to indicate similarity of
all properties of the joint set.   Using this basic assumption, the
delineation of structural domains can usually be made with regard
to the attitude of the joint sets only.

Boundaries of structural domains tend to coincide with major structural
features such as faults, shear zones, geological contacts, etc.,
Experience has shown, however, that where these features exist there
need not necessarily be a structural domain boundary; this primarily
depends on the relative age of the features and the deformational
history of the area.

Some of the main features that may form boundaries to structural domains
are as follows:

(i)   Major through-going deformational features such as faults
      and shear zones.   A zone on either side of these features
      usually exists which may differ from the regional pattern
      and the width of these zones should be recognized in the
      analyses.

(ii) Geological contacts between rocks which have very different
      physical and mechanical properties, such as contacts between
      sedimentary, igneous and metamorphic rocks.

(iii) Geological contacts between rocks which have very different
      physical and mechanical properties, such as contacts between
      sedimentary, igneous and metamorphic rocks.

(iv) Geological surfaces, such as unconformities, that separate rocks
      which are markedly different in age.

(v)   Major fold structure which result in joint patterns which differ
      from one limb of a fold to another; zones of contortion.

(vi) Hydrothermal alteration and other weathered or erosional zones
      (e.g. porphyry copper and molybdenum deposits.)

When determining structural domains one should consider in which dir-
ection the structural characteristics of the mass tend to vary.   The
accuracy of the structural domain determinations will depend, to a
large extent, upon the analyst's ability to assess the variations of
the structural characteristics from one part of the slope to the other
to evaluate what basic structural controls lead to such variation.
In this regard effort should be made to assess whether the geologic
structural controls in the area tend to result in geologic structural
variations that are vertical, horizontal or oblique across the site.

Due to the subjective nature of the problem, the validity of such an
assessment will depend greatly upon the analyst's knowledge of the
general geology and geological history of the area; also on his ability
to apply knowledge and experience in making practical assessments
pertaining to geological structure and related geological history.

4.3   EXTRAPOLATION AND INTERPOLATION OF GEOLOGIC STRUCTURAL DATA

4.3.1 Principles of Extrapolation and Interpolation of Geologic Data

The reliability of the prediction techniques used to assess if joint
characteristics are similar or different in parts of the rock
mass which are inaccessible or where information is limited, is
of great significance and warrants particular attention.

Interpretation of the three-dimensional geologic structural
aspects of a rock mass requires either that structural
interpolation be made between two known conditions or that
various forms of structural *extrapolation* be carried out from
known conditions to areas within the slope where information is
nominal or entirely unknown.   Hence, almost all structural
problems relating to engineering in rock require some form of
interpolation and/or extrapolation.   In rock slope design work

in particular, extrapolation of geologic structural character-
istics from a known condition on an existing rock slope to an
unknown condition, within the rock mass, for a proposed rock
slope is a common requirement.   How well this extrapolation is
performed has obvious practical implications.

If any degree of confidence is to be achieved in designing rock
slopes it must be shown whether the geological characteristics
can be expected to be the same or to differ, and in what way to
differ, in the other parts of the mass where information is not
available.

4.3.2   Regional Geology Considerations

Because of variations brought about by lithological changes,
occurrences of major geologic structural features, differential
stresses during deformation, etc., all elements in the basic
regional jointing geometry do not always form at every location.
One or more elements may fail to develop (Friedman, 1963).
The total geometry or regional pattern can, therefore, be con-
structed only after putting together information from many loc-
ations.   However, if the sample population is small and the
sample stations are few in number or are not sufficiently dis-
tributed to obtain a representative sample, only part of the
basic jointing configuration may be derived.

In this respect, effort should be made to obtain available
literature dealing with the regional geology.   One should
obtain knowledge of the regional jointing pattern and determine
how the regional pattern compares to the joint geometry in the
project area.   By merely showing that both of these are
similar, higher confidence limits for extrapolation of the
structures within the project area will be established.

4.3.3   Geological Mapping on a Continuous Basis

One cannot over emphasize the importance of acquiring geological
structural information on a reasonably continuous basis, or at
regular intervals as slopes are advanced.   Detail geological
mapping should be an integral part of engineering design
procedures as the project proceeds.

Structural mapping should be carried out at suitably spaced intervals depending upon the nature of the operation and the rate of advance of the rock face is being worked. Having a sufficient amount of geologic structural data on hand will greatly facilitate an understanding of the nature of the joint population in areas where the excavation will eventually be located.

An illustrative case is the structural analysis work in the Nchanga pit in Zambia where information from two different locations of the advancing pit slope, about 300 feet apart were compared (Piteau, 1973). Using the comparison, reasonably confident extrapolations were made of structural information from the existing pit to a point some 350 feet into the rock mass where the final slope was to be located.

4.4   STATISTICAL CONSIDERATIONS IN GEOLOGIC STRUCTURAL ANALYSES

In carrying out joint surveys, whether by a detailed line, joint set or other mapping method, some form of selective sampling method is usually involved. Provided the sampling method is consistent a formal procedure of *statistical sampling* is involved whereby the individual geological structures have a given chance of entering the sample.

In the initial stages of slope development joint surveys often are conducted on limited exposed rock surfaces, which are formed by outcrops, trenches, tunnels and borehole sides or cores. The measured joints which make up the *sample* are usually only a portion of those in any particular area of bedrock exposure, hence it is convenient to define another kind of population, the *sampled population*. The sampled population constitutes that population of structural features which are available for sampling, consisting of the potential structures visible on all actual exposures that the geologist succeeds in visiting and sampling (Whitten, 1961).

The sampled population in turn is only a small part of all the structural features or *target population* (Krumbein 1960). The target population is the population of structures of interest about which it is desired to draw conclusions. Other aspects relating to geological sampling as well as statistical analyses of geologic data are discussed

by Rosenfeld (1954), Koch and Link (1970), Pincus (1951 and 1953) and Davis (1973).

In all instances, the sample will have a bias depending on the attitude of the exposed face and the method of sampling. Inferences can generally be made on a rigorous statistical basis from sample to sampled population, but any extension of these inferences to the target population is a matter of judgement on the part of the analyst. Such extensions and/or extrapolation of the sample or sampled population seem reasonable, provided that the sampled and target populations are in the same structural domain.

5. ANALYSIS OF GEOLOGIC STRUCTURAL TRENDS

AND PATTERNS USING THE CUMULATIVE SUMS TECHNIQUE

The cumulative sums technique (Piteau and Russell, 1971) provides a rapid and precise method of determining major trends above or below a particular reference value which is selected and ascertaining both the magnitude and location of these variations. This technique has been used on several projects to determine specific orientation characteristics of a particular set of discontinuities that requires more definitive understanding of the behaviour in three-dimension's. Variations or trends in structure such as joints, foliation, bedding, etc. can be defined accurately and easily using this method. The specific uses are as follows:

(i)   to determine a reliable estimate of the mean dip and/or strike of particular geologic structure in each drill hole, bench, outcrop, etc.,

(ii)   to detect general changes in current mean strike or dip above and below the mean level of the particular geologic structural data

(iii)   to predict the average dip and/or strike of the geologic structure between drill holes, benches, outcrops, etc. on section and also in parts of the rock mass where drill hole, bench or outcrop structural data is not available, and

(iv)   to construct graphical geological sections from which the overall mean dip or strike of the geologic structure in question can be determined as well as other factors such as the degree of waviness of the structure, all of which are values that are required in the slope stability analysis.

The cusums method consists of subtracting a constant quantity, K, which is taken to be the mean value of strike or dip in the drill hole, etc. from each value of dip or strike at about ten-foot intervals along the drill holes, benches, etc. and accumulating the differences as each additional value is introduced. Successive accumulated differences are designated the

cumulative sums or *cusums* of the original sequence of strike or dip values. The resulting graph of these sums is designated the *cumulative sum plot.* The cusums analyses in boreholes, etc. is usually carried out using the mean strike or dip value of each diamond drill hole logged or bench mapped.

The structural interpretation is based on the average slope of the cusums plot. The steeper the curve, the further the mean strike or dip at any particular location is from the mean value K (i.e. the mean strike or dip for the entire drill hole, bench, etc.) The slope of the line (and hence the amount of deviation of the current mean dip from the overall mean value) can be easily calculated. The slope of the plotted line joining, let us say, the mth point and the nth point further along the series indicates the average difference from the reference value of all the results from $X_m + 1$ to X_n inclusive.

The current foliation dip ($\bar{X}$) over an interval of the cumulative sum plot is given by

$$\bar{X} = K + \frac{\text{change in the cumulative sum}}{\text{change in n}}$$

Determination of the current mean strike or dip along the drill hole, bench etc. is facilitated by construction of a template (based on simple calculations) which, through an array of angles, gives the actual deviation of the mean strike or dip based on the slope of the cusums curve. By simply overlaying the template on the cusums curve the current mean strike or dip of the structure in question is read directly from the template.

It is usually the case that very local deviations of the mean strike or dip are not significant. Therefore, for purposes of these analyses, variations of the mean strike or dip for intervals along the drill hole, bench, etc. of less than 50 feet are usually not considered.

Values of current mean strike or dip are plotted on Manhattan diagrams which clearly show the variation in current mean dip with respect to depth (in the case of drill holes) or surface location (with respect to benches our outcrops). Examples of this technique are given in the paper by Piteau and Russell (1971) herein enclosed.

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WORKSHOP PRACTICUM ON GEOLOGIC

STRUCTURAL ANALYSIS

APPENDIX C-1

PROBLEMS ON DEFINING JOINT SETS AND RELATED CHARACTERISTICS

1.   QUESTIONS

(a)   *Problem 1*: Plotting of Poles and Planes and Determining Geo-
      metric Relationships With Stereographic Projections.

   (i)   Using the equal area net provided, plot the poles and
         planes for the following joint measurements on the over-
         lay in Fig. 1.

	Strike	Dip
Plane A	035	68E
Plane B	108	22N
Plane C	135	80SW
Plane D	162	90
Plane E	67	50S

   (ii) It is assumed that Planes A and B form an unfavourable
         wedge.   Determine:

            -the angle (δ) between the poles of the planes
            -the interior angle (ω) of the wedge (between the
             planes
            -the bearing and plunge of the line of inter-
             section
            -the apparent dip of Plane A in Plane B
            -the pitch (β) of Plane A in Plane B.   Pitch is
             the angle in Plane B between the horizontal and
             Plane A.

         It should be noted that determining these parameters using

conventional geometry techniques would be very time consuming and would require construction of several detailed drawings.

(b) *Problem 2*: Contouring Scatter Diagrams and Defining the Orientation of Joint Sets.

For a given set of orientation measurements, the poles to the individual measurements can be plotted on a lower hemisphere projection, producing a scatter diagram such as the one shown in Fig. 2. If the scatter diagram is constructed using an equal area projection it is possible to contour the poles as to density on the net and determine if preferred orientations of geologic structure exist. In other words this process defines the joint sets. Density contours can further be used to examine the statistics of each joint set, i.e. define the mean, standard deviation, dispersion, etc.

(i) Using the transparent grid overlay and one percent circle template provided, complete the point counts for the scatter diagram shown in Fig. 2 using Fig. 3. Having completed the point count, contour the net using an appropriate number of contours. It should be noted that, because there are 50 measurements plotted, the percentage weight of each contour will be twice the number of points marked on the grid.

(ii) Record the average or peak orientation of each joint set and the percent concentration of poles at the peak.

(c) *Problem 3*: Contouring Scatter Diagrams and Defining the Orientation of Joint Sets.

The operations of plotting, counting and contouring structural orientation data are extremely time consuming. Use of computer programs significantly reduces the amount of labour involved and also allows more flexibility in sorting and comparing the data in defining structure domains, investigating for trends, etc.

(i) Figs. 4 and 5 are computer generated contour diagrams of orientation data, each number or letter refers to the percent area on the sphere. These figures were produced

N
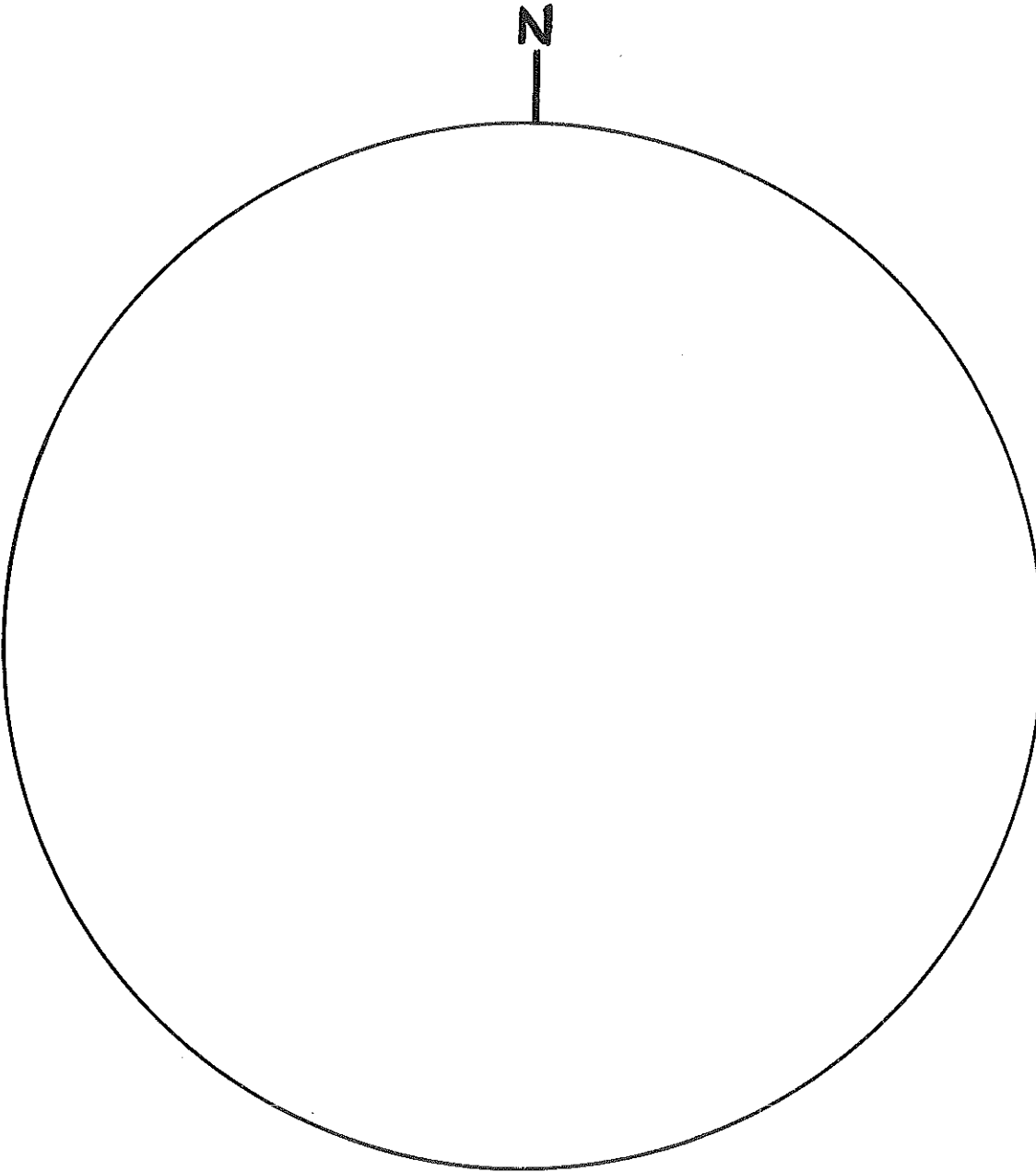
Fig. 1. Equal area net overlay for plotting poles and planes of structural discontinuities   (Blank 15 cm Stereonet for construction).
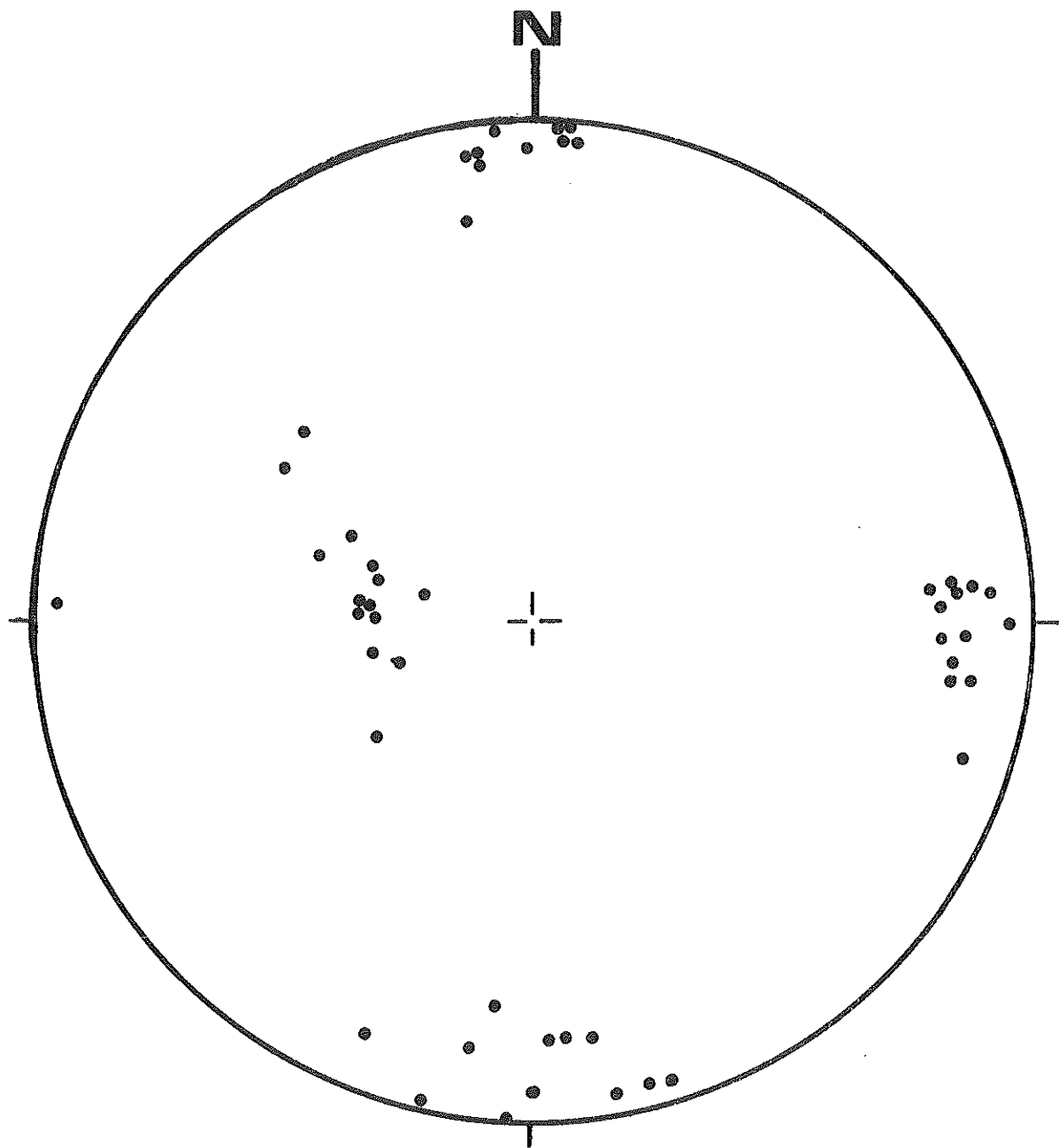
Fig. 2   Scatter diagram of equal area plot of poles to joints in a
rock mass.
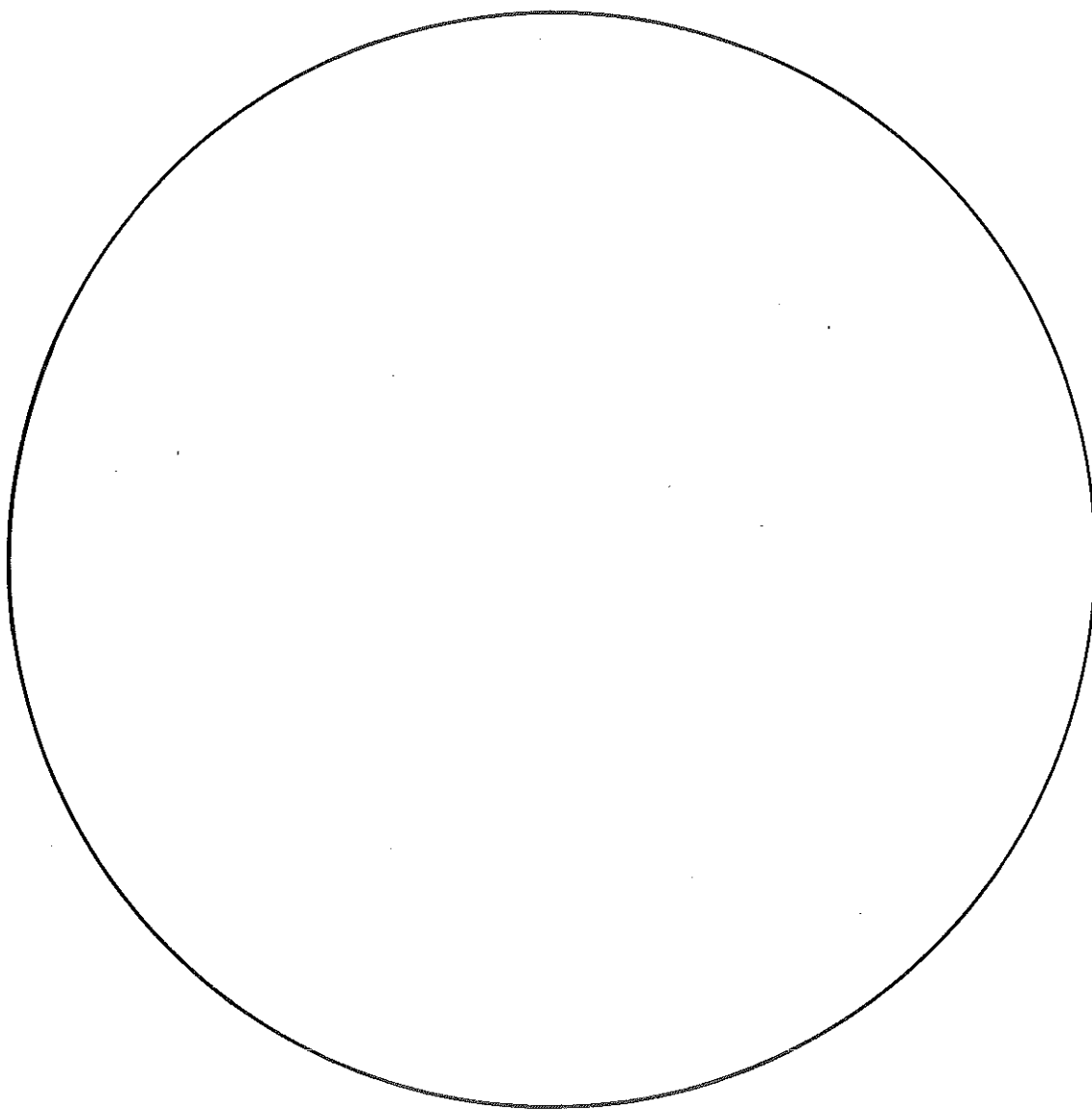
Fig. 3 (Blank net)

Equal area net overlay for point count and contouring scatter
diagram of poles to joints in a rock mass.

using a stereographic projection (Wulff net).   Contour
the printouts in Figs. 4 and 5 using an appropriate number
of contours according to the contour symbols given in
Fig. 6.   Also, determine the peak or average orientations
for each set.

(ii)   Figs. 7 and 8 are equal area projections (on a
       Schmidt Net) of two joint sets from typical joint
       mapping.   Contour these diagrams and determine the
       peak orientation of each joint set.

(d)   *Problem 4:*   Determination of Joint Dispersion Characteristics.

In many cases it is sufficient to design a slope based on the
average or peak orientation of the joint sets.   However,
in designing to the average dip orientation, for example, it
is assumed that **exactly 50%** of the orientations
steeper than the mean and 50% will be shallower than the mean.
If you were to design a slope to the average dip it is,
therefore, possible that under certain conditions one half
of the possible failures could become unstable.   Hence,
some information on the probability of obtaining a dis-
continuity with an orientation other than the average may
be required.

(i)   Examination of the statistical distribution of the
       joint sets in Fig. 4 was carried out by examining
       profiles of dip on the stereographic projections
       Construct a profile of dip values for Joint Set A
       and determine the probability of obtaining a joint
       of that set with a dip of 60°.   An enlargement of
       part of the stereonet in Fig. 4 is provided in Fig. 9
       for this exercise.

(ii)   The nature of the joint distributions in Figs. 7 and 8
       were examined visually by using the computer to rotate
       each joint set to the centre of the equal area net.
       By rotating the mean of the joint set to the centre
       of the equal area net and maintaining the other portions
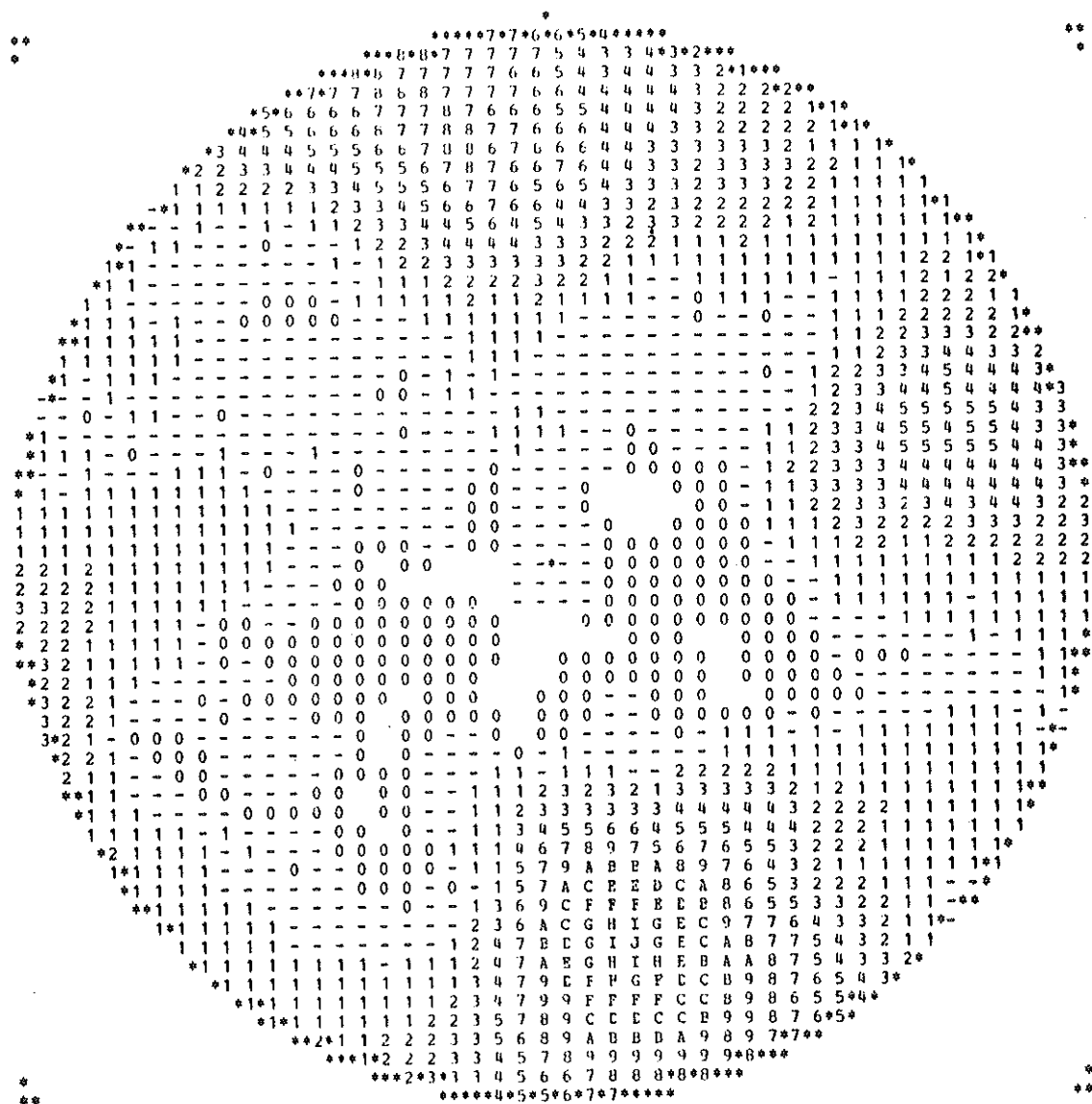
Fig. 4 Computer plotted equal angle Stereographic projection of
joints in a rock mass (565 obs)
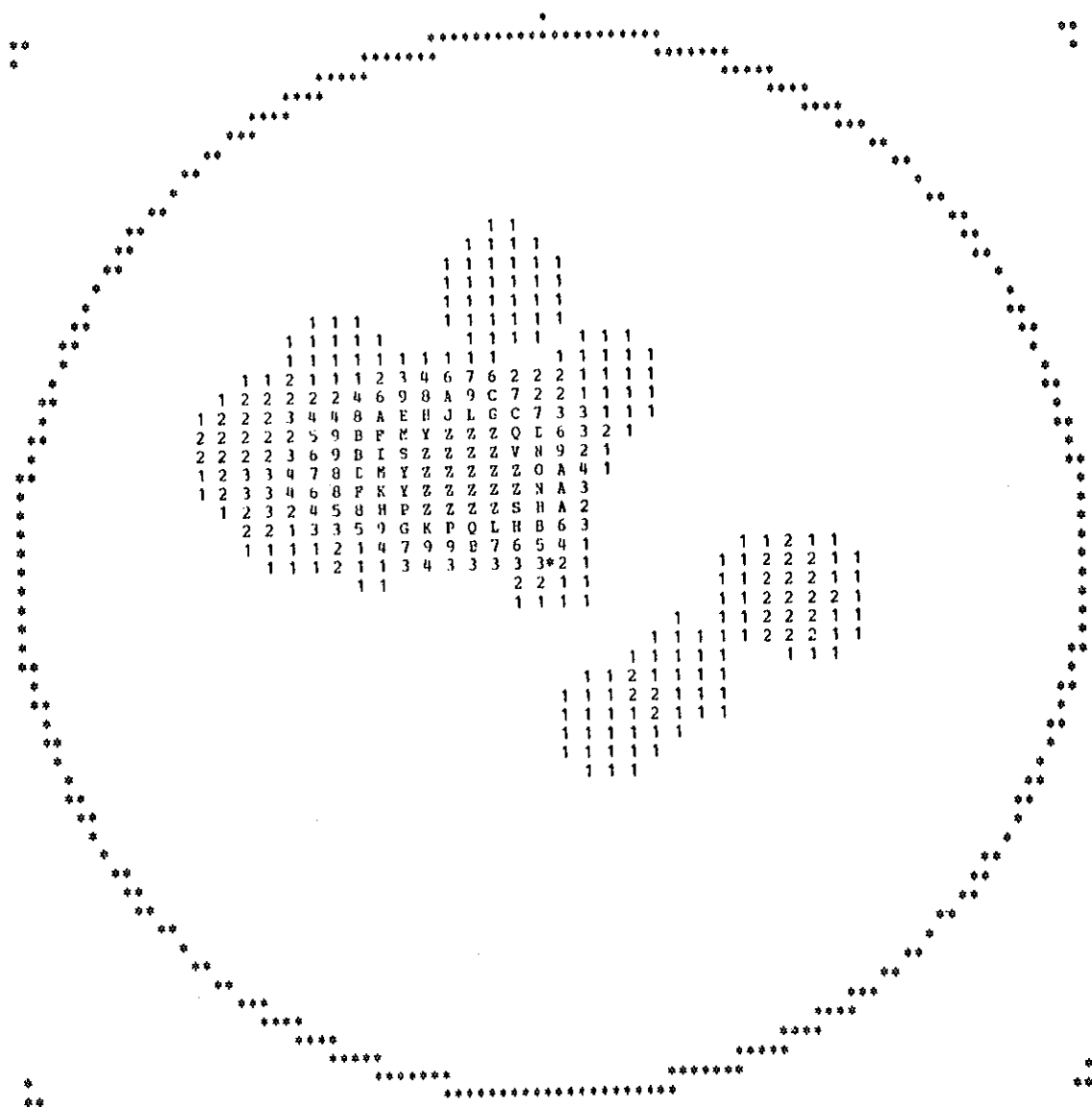
Fig. 5 Computer plotted equal angle Stereographic projection of
bedding in a rock mass (97 obs)

CONTOUR VALUES OF THE STEREOGRAPHIC PROJECTIONS

Prac. C-8

CONTOUR VALUE*	CHARACTER	CONTOUR SYMBOL
0 – 1		
1 – 2	1	
2 – 3	2	
3 – 4	3	
4 – 5	4	
5 – 6	5	
6 – 7	6	
7 – 8	7	
8 – 9	8	
9 – 10	9	
10 – 11	A	
11 – 15	B to E	
16 – 20	F to J	
21 – 25	K to O	
26 – 30	P to T	
31 – 35	U to Y	
> 35	Z	

*CONTOUR VALUES ARE EXPRESSED AS THE PERCENT OF THE TOTAL WEIGHT OCCURRING IN A 1.0 PERCENT AREA OF THE LOWER HEMISPHERE.

Fig. 6. Contour values of the lower hemisphere projections of structural data.

682 OBSERVATIONS WITH TOTAL WEIGHT OF   682.0
PERCENT OF TOTAL WEIGHT IN 1.0 PERCENT OF AREA
CONTOUR INTERVAL 1.0   CHARACTER SEQUENCE   123456789ABCDEFGHIJKLMNOPQRSTUVWXYZ****

```
                    1111
                  11111111
                111222222211
               122344545443211
              123456777664332111111
             134668999999886432222111
             1123568ABDCCCCBA87554333221
             1134678ACDDEEFECB977644333311
            11224779BCDEFGHHFCA887555554321
           1122345689ACDEEEGHFECA9876664443211
          1112234566888ABBBDDEEEDB987666555532211
         111233566877888ACDEEDEEC9887877775432211
         111234455667777878 9A EBBBAA986677665433 1
        1112234455544566766899988888778777664321
        112233344444444455567767777787788876543211
        111222323334444433335445555556666544443211
         1111222233322333333333334434433333321 1
           111222222222222121222211  111
                11111111
```

Fig. 7 Computer plotted equal area projection of foliation joints in
        a rock mass. (682 obs)

440 OBSERVATIONS WITH TOTAL WEIGHT OF   440.0
PERCENT OF TOTAL WEIGHT IN 1.0 PERCENT OF AREA
CONTOUR INTERVAL 1.0   CHARACTER SEQUENCE   123456789ABCDEFGHIJKLMNOPQRSTUVWXYZ****

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             1223344566654321
             12246689AAA8764211
            114678BDFFEFCA854221
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          249CGIMNRQQQPMJFBA764321
         1259CHJMPQRRSROMJEC8864211
         268BEGKMPOQPRPLJHEC865432
         13689BGJHJMOPOJIIEC9764321
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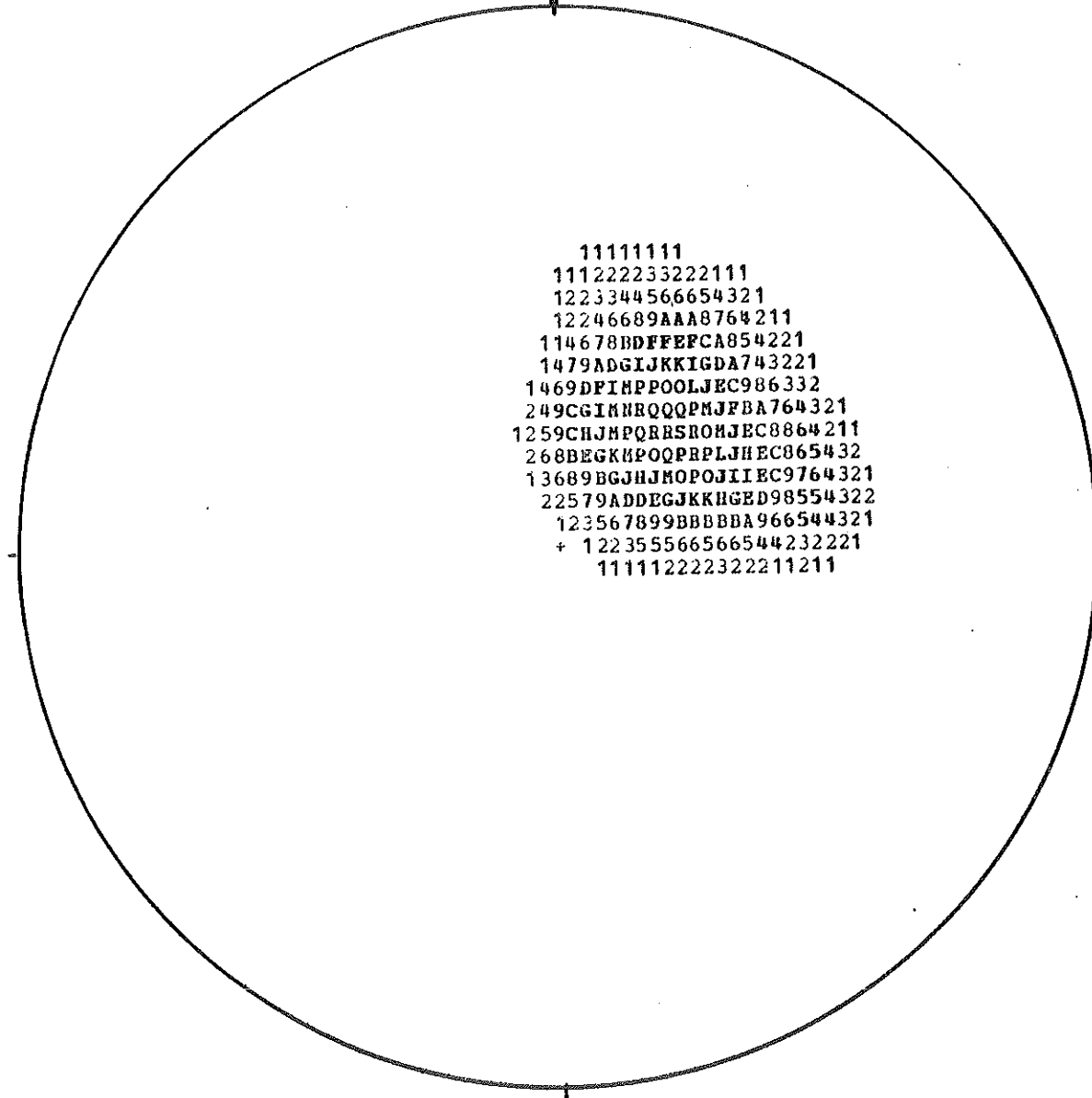
Fig. 8 Computer plotted equal area projection of a joint set in a
        rock mass   (440 obs)

Fig. 9 Enlarged portion of computer plotted projection of joints from Fig. 4 showing line for taking profile of Joint Set A.
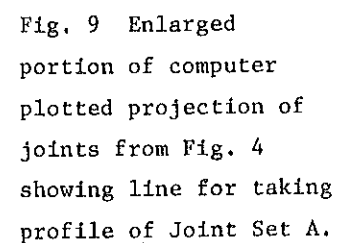
of the distribution in their same relative position
(i.e. by rotating along the small circles of the net),
a relatively undistorted representation of the joint
set would be obtained. The peak concentration should
occur at the centre of the net and the density contours
should be approximately circular and concentric about
the mean. In the analysis the mean of the joint
vectors (Fisher Mean) was used for rotation to the
centre of the net. Using the printout of the rotated
joint sets in Fig. 10 and 11 contour and evaluate the
resulting joint distributions.

(e)   *Problem 5:* Assessment of Continuity of Joints Using Histograms

Although information from the field mapping data alone cannot be
used to determine the absolute strength properties, such as
cohesion, friction, etc. which are determined from testing in the
laboratory, the joint survey mapping information can result in
defining some of the other important physical characteristics, some
of which have a direct bearing on the C and $\emptyset$ values.

(i)   Given in Fig. 12 is a histogram of the relative freq-
            uency and cumulative frequency distribution of joint
            continuity of 1394 joints, occurring in sedimentary
            rock (argillite) with no ends out (i.e. both joint ends
            along the dip can be seen). What is the relative
            frequency of joints with joint lengths of 5 ft and 10 ft?
            What percentage and number of joints are greater than
            5 ft and 10 ft length?

(ii)   To find an equation which could apply to the frequency
            distribution of joint continuity, since both ends of
            the joint could be seen, it was considered that the
            dip continuity with no ends out was the reasonable data
            to use. What frequency distribution of dip continuity
            appears best to fit the data in Fig. 12? If this is
            a typical distribution, what is its significance?

```
         - 'FISHEP' MEAN AT CENTRE
   682 ORSERVATIONS WITH TOTAL WEIGHT OF    682.0
  PERCENT OF TOTAL WEIGHT IN  1.9 PERCENT OF AREA
  CONTOUR INTERVAL  1.0    CHARACTER SEQUENCE   123456789ABCDEFGHIJKLMNOPQRSTUVWXYZ****
```



```
                         111
                        111111
                      11222222111
                    11234344432111
                   123456776654321111.
                  11356789899998754422111
                  23567ABCCCCBB9754332211
                  23579BCDEDDECA8766433321
                 12467AABCEFGHPDC9865444321
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               12344678889BCE+GEDBA8666554321
              1123467888889BBDCDCAA8876665321
             223356677777778AABAA997667653211
            11234556655667678998788777664221
            11223455544555567767778877764321
            11123444444333344556667778876542 1
            111233233344333333344546676654321
             112222.23322333322234344444443311
             111112222222222211122211122232211
               1111221111
                  111
```

Fig. 10   Computer plotted equal area projection of the foliation joints
          in Fig. 7 rotated to the centre of the net.

```
     - 'FISHER' MEAN AT CENTRE
440 OBSERVATIONS WITH TOTAL WEIGHT OF    440.0
PERCENT OF TOTAL WEIGHT IN   1.0 PERCENT OF AREA
CONTOUR INTERVAL  1.0    CHARACTER SEQUENCE  .123456789ABCDEFGHIJKLMNOPQRSTUVWXYZ****
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          123334556554322
          1234668A9A9764311
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        13579CEHIIJIGDA853221
        1358CEHLNOOOMIFC9854321
        148DFILNQQRPOMHEBA764321
        259DHJLPRRS*ROLHEC9764221
        268CFHLOQPQPRQLJHEC8754321
        24789DJKIMNNPOJJIEC9765422
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          12234566765665532222211
           1111222322322111111
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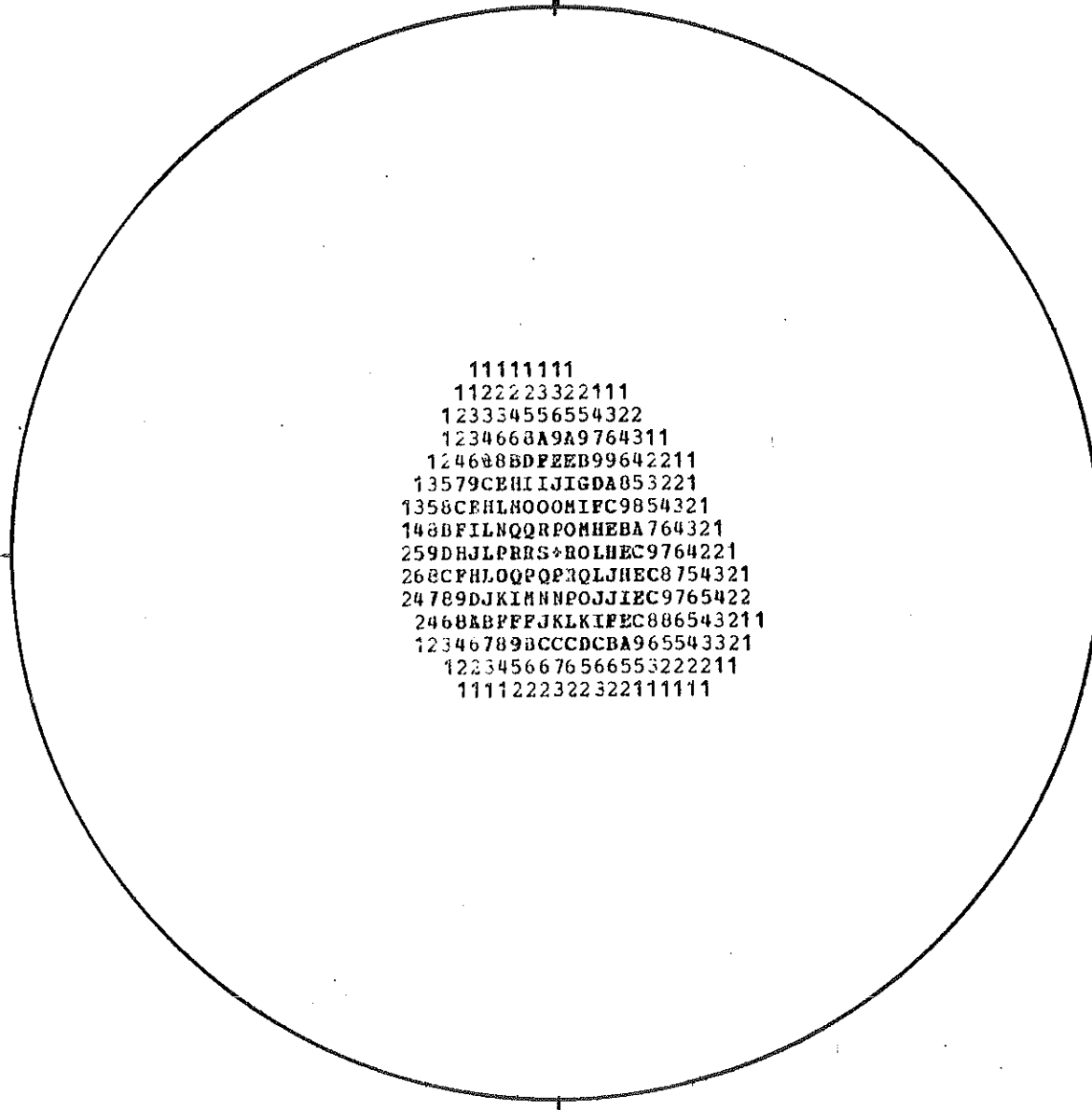
Fig. 11   Computer plotted equal area projection of joint set in Fig. 8
          rotated to the centre of the net.

```
STATISTICAL SUMMARY

NO. OF POINTS IS  1394

MINIMUM =      1.000000 MEAN =       4.746055 MAXIMUM =      40.000000

MOMENTS ABOUT THE MEAN
         SECOND(I.E. VARIANCE)= 1.7795029160 01   ST. DEV. =      4.218415
         THIRD MOMENT         = 2.0320395000 02   SKEWNESS =      2.706974
         FOURTH MOMENT        = 4.1347223690 03   KURTOSIS =     13.057167

SIZE
UPPER  FREQ REL   CUM   I          RELATIVE FREQUENCY DIAGRAM          I          CUMULATIVE FREQUENCY DIAGRAM
LIMIT       FREQ  FREQ  I                                              I
  0.0     9  0.0   0.0  I                                              I
  1.000 120  8.61  8.61 I#############################                 I####
  2.000 313 22.45 31.06 I############################################# I########################
  3.000 292 20.95 52.01 I###########################################   I#############################
  4.000 188 13.49 65.49 I#######################                       I#############################
  5.000 141 10.11 75.61 I##################                            I#############################
  6.000  80  5.74 81.35 I##########                                    I###############################
  7.000  34  2.44 83.79 I#####                                         I#############################
  9.000  59  4.23 88.02 I########                                      I#############################
  9.000   2  0.14 88.16 I                                              I#############################
 10.000  63  4.52 92.68 I#########                                     I#############################
 11.000   1  0.07 92.75 I                                              I#############################
 12.000  24  1.72 94.48 I####                                          I#############################
 13.000   5  0.36 94.83 I#                                             I#############################
 14.000   2  0.14 94.98 I                                              I#############################
 15.000  31  2.22 97.20 I#####                                         I#############################
 16.000   1  0.07 97.27 I                                              I#############################
 17.000   1  0.07 97.35 I                                              I#############################
 18.000   3  0.22 97.56 I                                              I#############################
 19.000   0  0.0  97.56 I                                              I#############################
 20.000  23  1.65 99.21 I####                                          I#############################
 21.000   0  0.0  99.21 I                                              I#############################
 22.000   0  0.0  99.21 I                                              I#############################
 23.000   0  0.0  99.21 I                                              I#############################
 24.000   0  0.0  99.21 I                                              I#############################
 25.000   9  0.65 99.86 I#                                             I#############################
 26.000   0  0.0  99.86 I                                              I#############################
 27.000   0  0.0  99.86 I                                              I#############################
 28.000   0  0.0  99.86 I                                              I#############################
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 30.000   1  0.07 99.93 I                                              I#############################
 31.000   0  0.0  99.93 I                                              I#############################
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 36.000   0  0.0  99.93 I                                              I#############################
 37.000   0  0.0  99.93 I                                              I#############################
 38.000   0  0.0  99.93 I                                              I#############################
 39.000   0  0.0  99.93 I                                              I#############################
 NONE     1  0.07 100.00 I                                             I#############################
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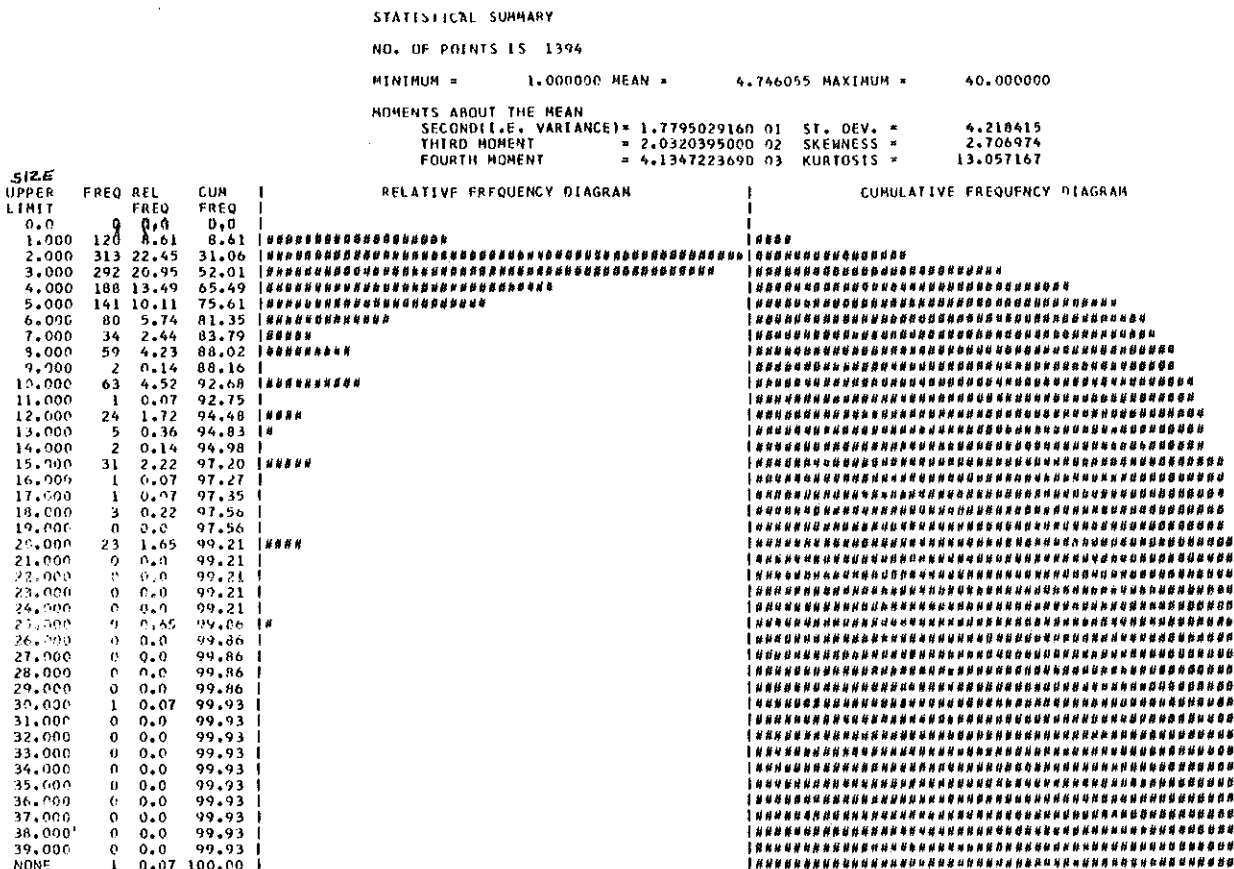
Fig. 12 Histogram of the relative frequency and cumulative frequency distribution of joint continuity of joints with no ends out (i.e. both joint ends along the dip can be seen)

```
STATISTICAL SUMMARY

NO. OF POINTS IS  3844

MINIMUM =      3.000000 MEAN =       6.886056 MAXIMUM =      11.000000

MOMENTS ABOUT THE MEAN
         SECOND(I.E. VARIANCE)= 1.1026237930 00   ST. DEV. =      1.050059
         THIRD MOMENT         = 7.4286150460-01   SKEWNESS =      0.641604
         FOURTH MOMENT        = 3.9144400760 00   KURTOSIS =      3.219696

HARDNESS
UPPER  FREQ REL   CUM   I          RELATIVE FREQUENCY DIAGRAM          I          CUMULATIVE FREQUENCY DIAGRAM
LIMIT       FREQ  FREQ  I                                              I
  2.000    0  0.0   0.0  I                                             I
  3.000    6  0.16  0.16 I                                             I
  4.000    4  0.10  0.26 I                                             I
  5.000   68  1.77  2.03 I##                                           I#
  6.000 1686 43.86 45.89 I########################################     I##################
  7.000  995 25.88 71.77 I######################                       I######################
  8.000  792 20.60 92.38 I##################                           I###########################
  9.000  262  6.82 99.19 I########                                     I###########################
 10.000   20  0.52 99.71 I#                                            I###########################
 NONE     11  0.29 100.00 I                                            I###########################
```
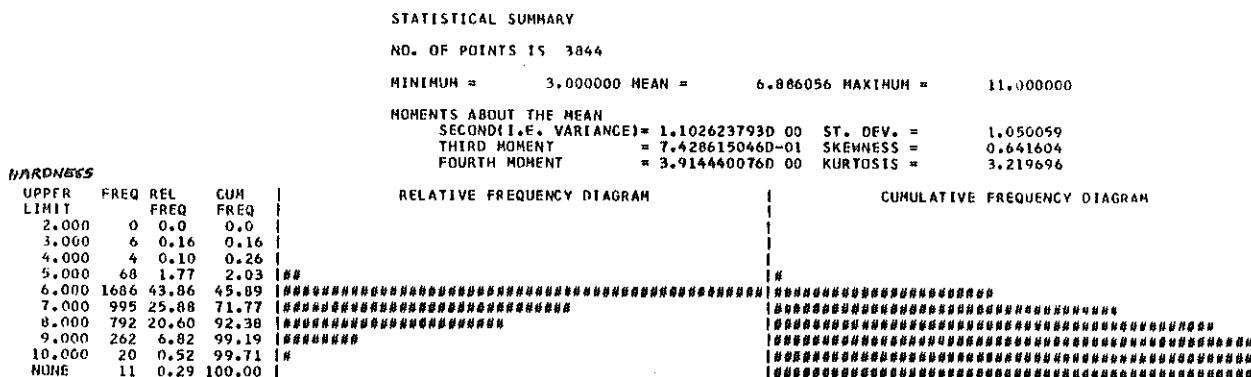
Fig. 13 Histogram of relative frequency and cumulative frequency distribution of joint wall rock hardness.

(f)   *Problem 6:*   Assessment of Hardness and Unconfined Compressive Strength Using Histograms.

(i)   Given in Fig. 13 is a histogram of the relative frequency and cumulative frequency distribution of ten categories of joint wall rock hardness (i.e. S1 to S5 and R1 to R5) where an arbitrary numerical value of 1.0 is given to hardness R5. Of the 3844 joints considered in the analysis, what percentage of joint surfaces are softer than hardness R2?

(ii)   If the mean hardness is 6.89, what percentage of the respective hardness category does this represent and accordingly what is the approximate mean unconfined compressive strength based on the values shown in Fig.14?

(g)   *Problem 7:*   Analysis of Geologic Structural Data Using the Cumulative Sums Technique

(i)   Given in Fig. 15 (a) is a plot of raw direction of dip data of a dominant joint set on a bench in sedimentary rocks. Fig. 15 (b) shows a plot of the cusums values of the raw data which is displayed in Fig. 15 (a). Using Fig. 15 (b) determine the current mean direction of dip values along the bench and construct the Manhattan Diagram in Fig. 15 (c), giving the current mean direction of dip of the joint set across the bench in question.

(ii)   Given in Fig. 16 are cumulative sums plots for both direction of dip and dip for two joint sets going from east to west along a bench. In the appropriate location on the drawing note the mean dip and mean direction of dip for the four separate cusums curves. Also, construct the Manhattan diagram at the bottom of the plots for the four cusums curves.

(iii)   Given in Fig. 17 is the complete set of Manhattan diagrams for the strike values of a dominant joint set on ten benches in a high slope in argillite. Given at the bottom of the figure is the average mean strike

values of the joint set for all ten benches for different
areas along the wall.   Discuss these average results,
noting the trend, if any, and other significant geological
aspects such as degree of confidence or reasons why
extrapolation of the joint population in an easterly
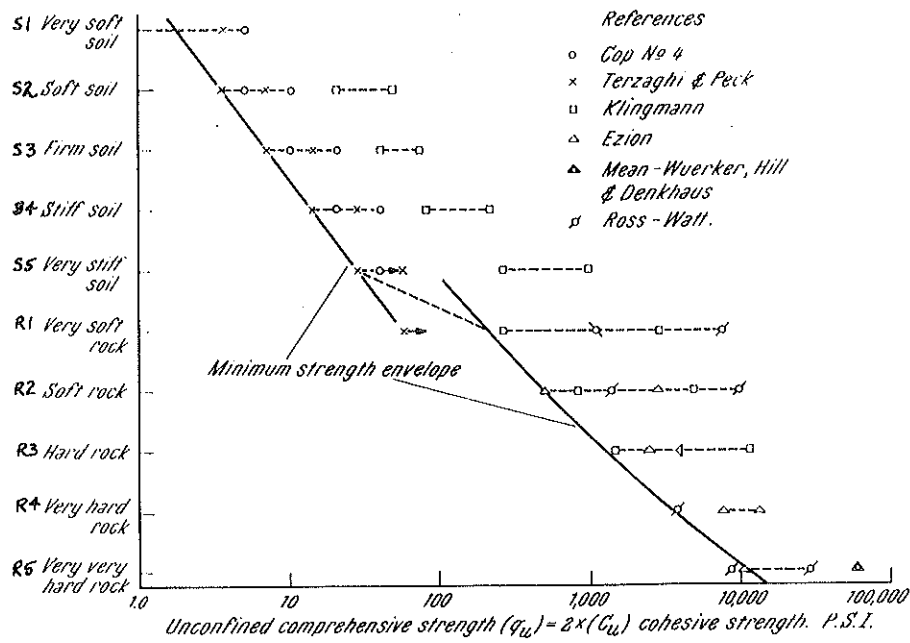direction is or is not feasible.

Fig. 14 Relationship between consistency or hardness as classified in the joint survey and unconfined compressive strength of the material.